Data Analysis in High-Energy Physics with Quantum Computers

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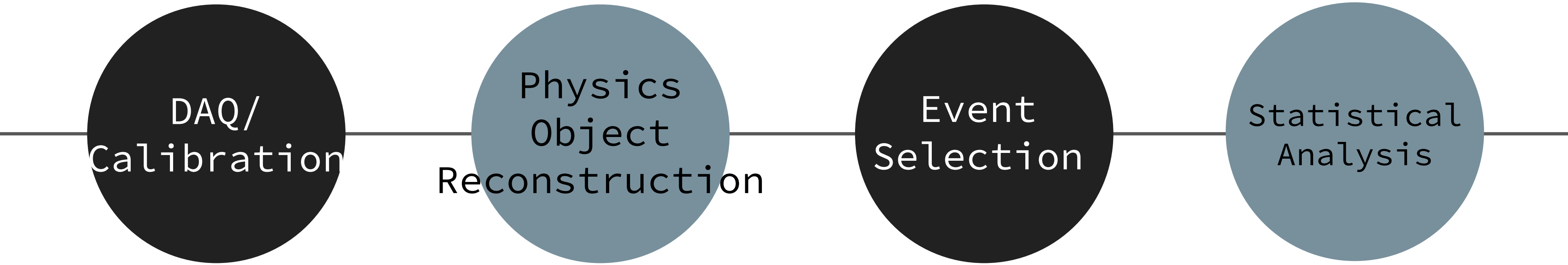
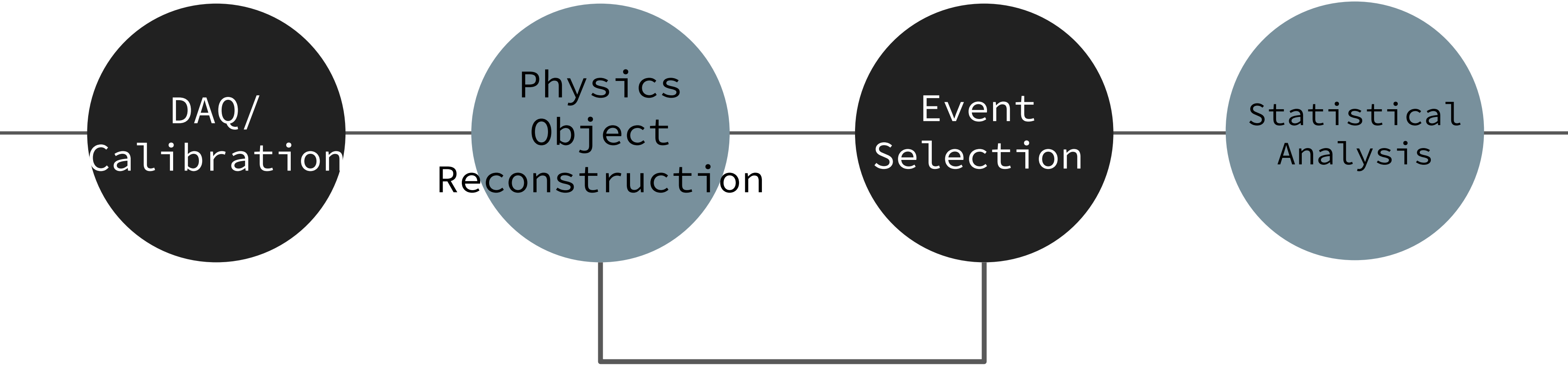
Overview


DAQ/
Calibration
Physics
Object
Reconstruction
Event
Selection
Statistical
Analysis

Overview

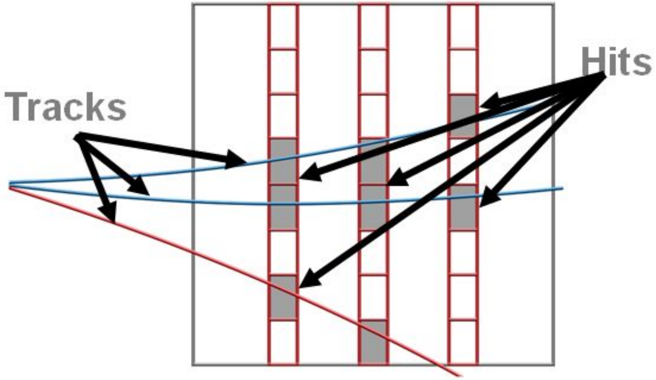


The main focus of this talk!

Object Reconstruction

Track Reconstruction

- ***“Connecting the dots”*** problem: Assign detector **“hits”** to **“so-called”** tracks to reconstruct the trajectory of a charged particle through the detector.
- An essential step in the reconstruction of **higher level objects** (*muons, jets, etc.*).
- A key **computing challenge** for future collider experiments.
  - More data = an increase in running time for conventional algorithms.

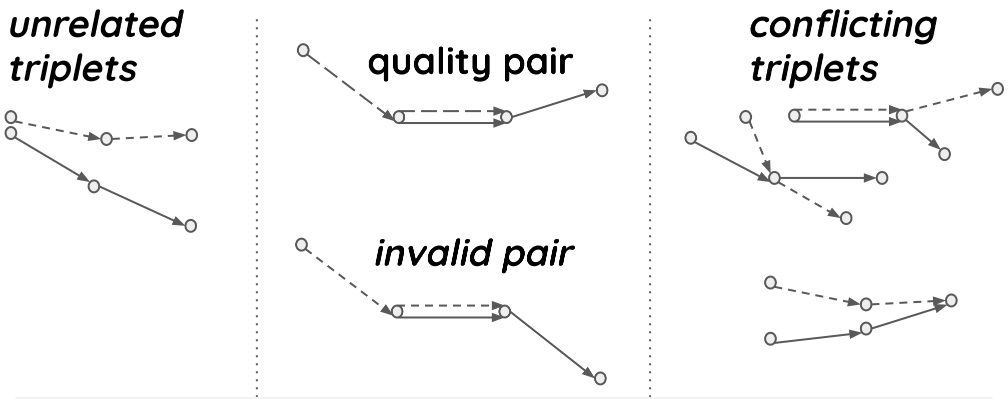


Reconstruction complexity scales with detector granularity and track multiplicity.

A Pattern Recognition Algorithm for Quantum Annealers

F. Bapst, W. Bhimji, P. Calafiura, H. Gray, W. Lavrijsen, L. Linder arXiv:1902.08324

- **Track reconstruction** problem formulated as a **QUBO**, solved via **quantum annealing**.
- Tested algorithm on **TrackML** challenge (*a dataset representative of the expected conditions at the HL-LHC*)
- After some pre-processing of the data, generate a set of potential **triplets**.
- **Binary classification** task to determine which triplets should be kept in the track candidates.



$$E = \alpha\Big(\sum_{i}^{N} T_i\Big) - \Big(\sum_{i,j(\in pairs)} S_{ij}T_iT_j\Big) + \zeta\Big(\sum_{i,k(\in conflicts)} T_iT_k\Big) \quad T \in \{0,1\}$$

“***bias weight***” triplet prior can be set to 0

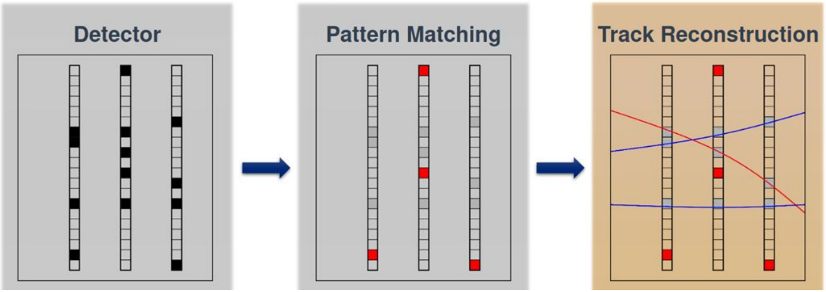
“***connection strength***”, interest of [keeping] a pair of triplets

avoid “***conflicts***”, a hit belongs to at most one track

Pattern Track Classification Using Quantum Content Addressable Memory

Andrea Delgado, Travis S. Humble, Lauren Ice, Gregory Quiroz

Pattern matching algorithm quickly identifies potential track candidates by comparing detector signals to a "library" of pre-computed patterns.



If we have a set of m patterns and keys:

Pattern: $V = [v^{(1)}, v^{(2)}, \dots, v^{(m)}]^T$ ***m* - patterns of length *n***

Keys: $K = [k^{(1)}, k^{(2)}, \dots, k^{(m)}]^T$ **keys are set to 1**

We can use the following learning rule:

$$W = \begin{pmatrix} 0 & W_B \\ W_B^T & 0 \end{pmatrix} \qquad W_B = \frac{1}{n} K^T V$$

Hebbs Learning Rule

To encode the recall problem as an adiabatic quantum optimization problem via the Hamiltonian:

$$H(t, \theta) = A(t) H_X + B(t) H_\theta$$

initial Hamiltonian

template to match

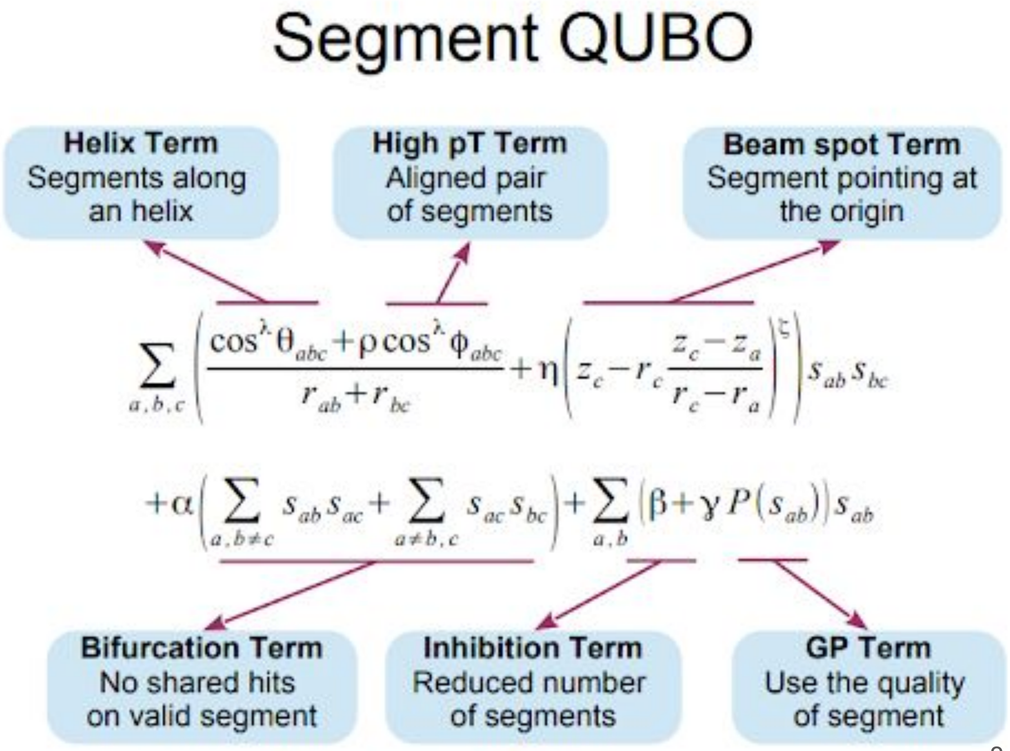
$$H_\theta = -\sum_{i,j}^{n} w_{ij} \sigma_i^z \sigma_j^z - \sum_i^n \theta_i v_i^{(0)} \sigma_i^z$$

Which is then solved by using D-Wave's quantum annealer

Charged Particle Tracking with Quantum Annealing-Inspired Optimization

A. Zlokapa, A. Anand, J.R. Vilmant, J. M. Duarte, J. Job, D. Lidar, M. Spiropulu, [arXiv: 1908.04475](https://arxiv.org/abs/1908.04475)

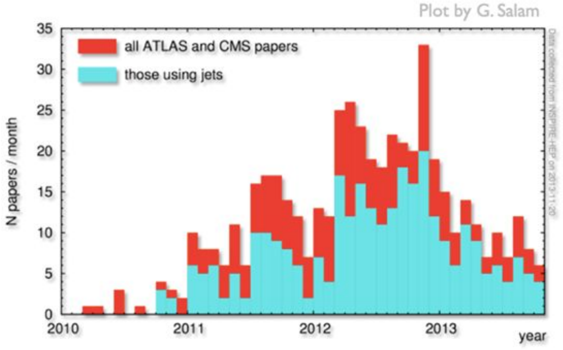
- Adapted version of **Denby-Peterson (Hopfield) network** method to the quantum annealing framework and to HL-LHC conditions.
- Segment = pair of hits on consecutive layers of the detector.
- Assign a boolean to each segment representing whether the segment is within a track or not.
- Minimize the energy associated with each network configuration (assignment of unit/vertices).



Quantum-Assisted Algorithms for Jet Clustering

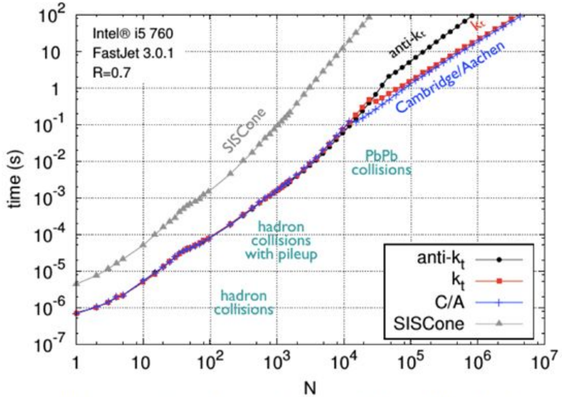
Annie Y. Wei, Preksha Naik, Aram W. Harrow, Jesse Thaler

> 50% of papers published by CMS and ATLAS make use of jets (according to INSPIRE)



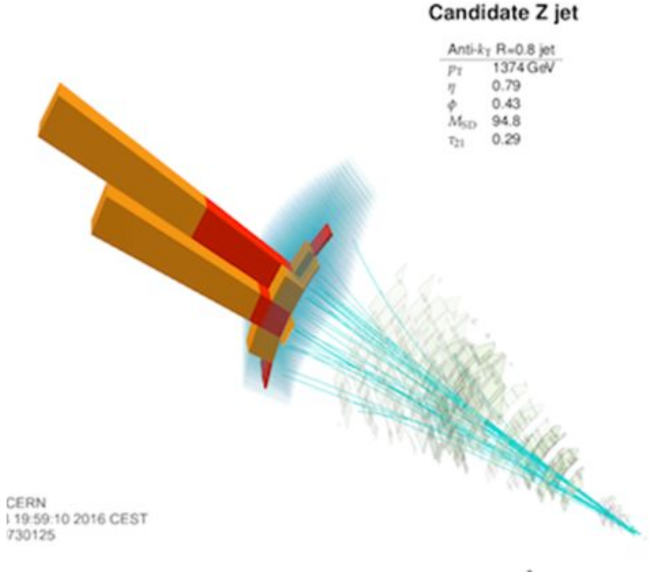
Jets are an important tool for HEP analyses!

Time needed to cluster an event with N particles



Jet reconstruction is a computationally intensive task, as it often includes performing **optimizations** over potentially large numbers of final state particles

Jets - Experimental signature of quarks and gluons



Quantum-Assisted Algorithms for Jet Clustering

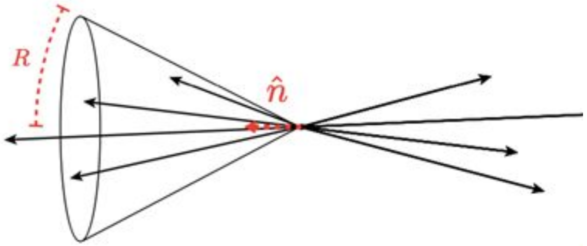
Annie Y. Wei, Preksha Naik, Aram W. Harrow, Jesse Thaler, [arXiv: 1908.08949]

- The SINGLECONE algorithm finds a single stable-cone with radius R.

  In QUBO formulation:

$$O_{QUBO} = \sum_{i,j}^{N} \left(\frac{\vec{p_i} \cdot \vec{p_j} - E_i E_j \cos R}{1 - \cos R} \right) x_i x_j$$

Binary assignment to either the clustered or un-clustered region



- For M-jets, we can do a one-hot encoding per particle to indicate their assignment to one of the M jet regions or the un-clustered region.

$$O_{QUBO} = \sum_{r=1}^{M} \sum_{i,j}^{N} \left(\frac{\vec{p_i} \cdot \vec{p_j} - E_i E_j \cos R}{1 - \cos R} \right) x_{ir} x_{jr} + \lambda^2 \sum_{i=1}^{N} \left(1 - \sum_{r=0}^{M} x_{ir} \right)^2$$

Lagrange multiplier

Penalty term added to discourage the assignment of one particle to more than one jet

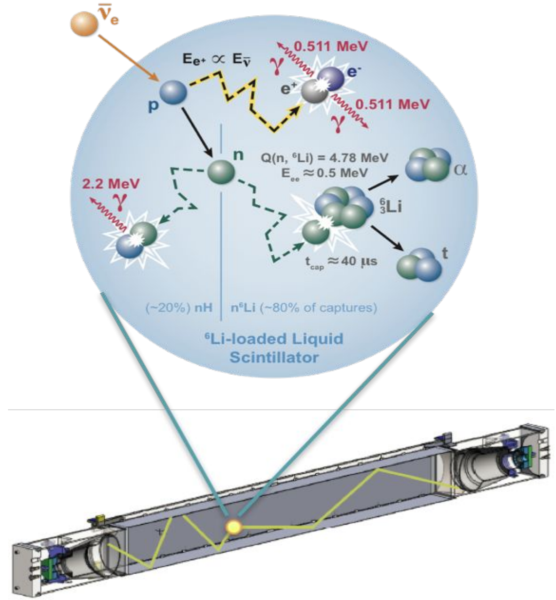
Quantum-Assisted Algorithm for Inverse-Beta Decay Event Reconstruction

Andrea Delgado, Alfredo Galindo-Uribarri, Travis S. Humble

- **Earth mover's distance (EMD)** is a measure of the distance between two probability distributions over a region.
- Cast the problem of minimizing the cost of "turning one pile of dirt into another" to an Ising Hamiltonian, which can then be solved via quantum annealing.

$$\mathrm{EMD}(\mathbf{x},\mathbf{y}) = \frac{\min_{F=(f_{ij})\in\mathcal{F}(\mathbf{x},\mathbf{y})} \mathrm{WORK}(F,\mathbf{x},\mathbf{y})}{\min(w_\Sigma, u_\Sigma)}$$

The minimum cost of turning one pile of dirt into another



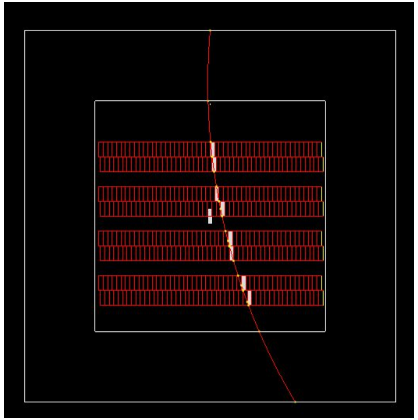
Antineutrinos detected through Inverse Beta Decay (IBD) interaction

Prompt signal: ~1-10 MeV positron energy
Delayed signal: ~ 0.5 MeV neutron capture

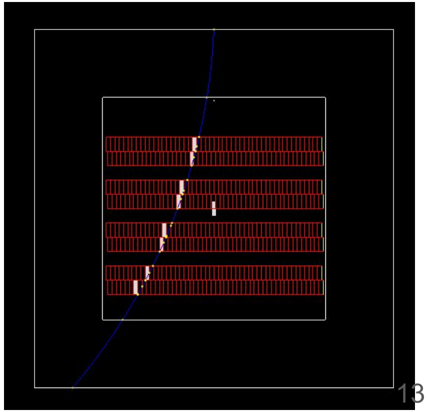
Event Selection/Classification

Quantum Restricted Boltzmann Machine for Particle Track Classification

Andrea Delgado, Travis S. Humble, Alex J. McCaskey, Anthony M. Santana



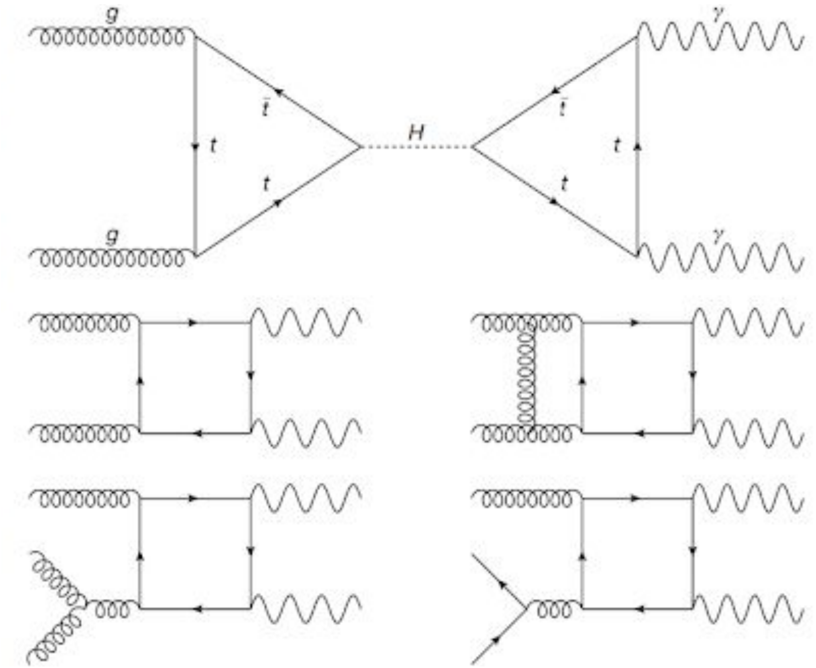
- Can we use QML for real-time classification of charged particle tracks?
- Use Quantum Restricted Boltzmann Machine (QRBM) as classifier.
    - Input to classifier in the form of images.
    - Sample and compress the images to ~½ of their size.
    - Compressed images are then the input nodes of the QRBM.
    - Weights of the nodes are physically represented as the coupling strength between qubits in the quantum annealer.
    - Iteratively solve for the ground state of the system to solve classification problem.



Solving a Higgs Optimization Problem With Quantum Annealing for Machine Learning

Alex Mott, Joshua Job, Jean-Roch Vilmant, Daniel Lidar, Maria Spiropulu

- Use a hybrid (quantum + classical) annealing to solve a Higgs signal vs background machine learning optimization problem.
- Classification problem is mapped to finding the ground state of an Ising Hamiltonian.
- Weak classifiers are based on the kinematic observables of the Higgs decay photons, which are then used to construct a strong classifier.



Summary

- **Quantum Computing can play an important role in HEP.**
  - **Taking first steps to understand and assess impacts and potential contributions to QIS.**
- **Is there quantum advantage for handling LHC-scale data?**
- **Hybrid (quantum-classical) algorithms might be a good way to start rethinking our analysis workflow.**

Thank you!

Questions?